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A SHOCK-TUBE-BASED FACILITY FOR IMPACT TESTING

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Abstract

Many dynamic testing techniques use gas guns as a pressure generator. The pressure generated from the gas guns is often of low velocity and low energy and has a relatively random or short duration of a uniform pressure level. This kind of pressure is not well defined and cannot be converted into other application conditions. With aims at improving experimental capability and expanding the research horizon, a shock tube was designed and constructed; and innovative applications were explored. With proper adjustments of gas components and gas pressures, well-defined pressure sources could be produced. With appropriate designs of a force transformer, various testing parameters required for different, dynamic experiments could also be simulated. In this paper, a piston-like impactor was inserted into the shock tube as a pressure transformer. The feasibility of using the shock-tube-based facility for impact testing was demonstrated.

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Introduction

Many dynamic testing techniques use a drop-weight tower or gas gun as a pressure wave generator [1-3]. The pressure wave produced from these generators is often of low velocity or low energy and has a relatively random or short duration of constant pressure. It is not easy to use or to modify this pressure wave for delicate applications. In order to convert a pressure wave into a specific pressure source for testing purpose, the pressure wave must be well defined. This will achieve a high-velocity, high-energy and/or high-temperature testing condition. Due to its promise in meeting both goals, a shock tube was designed and built as a pressure wave generator in the present study.

The first shock tube was built in 1861 [4]. In 1899, French chemist P. Vieille used a shock tube to study an explosion problem in combustion. He obtained a shock wave with a speed as high as 600 m/s in air. However, it was not until 1940 that Payman and other scientists started to study more carefully the flow in shock tubes. They extended the uses of shock tubes to pressure calibration and wave propagation. It took nine more years for the application of shock tubes to aerodynamic testing and the development of shock tunnels. Today, the shock tube is a multi-purpose, experimental facility which incorporates the design of shock tube and the shock-tube-related research as a special discipline.

Shock tubes are primarily used as supersonic wind tunnels in aerodynamic investigations [5]. Recently, Tekalur and Shukla [6] have used a shock tube for blast testing. In this study because of their high power and well defined properties, the exploration of shock tubes for general mechanical testing is of interest. The pressure wave generated from a shock tube can be directly applied to material testing. It is also possible to add a pressure transformer to the pressure generator to convert the pressure wave into a useful testing force. For example, a piston can be added to the shock tube for crash testing or a nozzle can be added to the shock tube for blast simulation. It is also important to indicate that the durations of the step waves with constant pressures produced from the shock tube can be around several milliseconds, as opposed to a few microseconds produced from the conventional gas gun technology. Hence, the shock tube is very useful for engineering calibrations, simulations, and applications involving dynamic loading.

The Pressure Generator – a shock tube

A shock tube is essentially a circular cylinder divided into two sections by a diaphragm. Figure 1 shows the three-section shock tube designed and built in this study, while Figure 2(a) is a schematic diagram of the unit. The shock tube is made of a steel alloy containing chromium and manganese and has high-strength and high-temperature resistance. It has a constant, cross-sectional area. The outer diameter of the tube is 120 mm, while the inner diameter is 80 mm. The total length of the shock tube is 6.1m. The left section, 2 m long, stores a relatively high pressure gas and is called the high-pressure chamber. The high-pressure gas is used to push the low-pressure gas forward and is also called the driving gas. The right section, 4 m long (consisting of two parts joined by flanges, each 2 m), stores a relatively low pressure gas and is called the low-pressure chamber. The low-pressure gas is used directly for testing and is also called the application gas. The third section, called the diaphragm chamber, is located between the high-pressure chamber and the low-pressure chamber and has a length of 0.1m. Two well-crafted diaphragms are used to isolate the diaphragm chamber from the high-pressure chamber and the low-pressure chamber.

At time t_0, the initial pressure in the high-pressure chamber is designated as P_4 while that in the low-pressure chamber is designated as P_1, as shown in Figure 2(b). In order to produce a shock wave, the diaphragms between the high-pressure chamber and the low-pressure chamber need to be removed instantaneously. Removing techniques based on electrification and explosion methods are often used. A third technique, which was used in this study, is based on the diaphragm chamber shown in Figure 2(a). The diaphragm chamber, as mentioned earlier is bounded by two diaphragms (one at each end) and is used to store a gas with a pressure approximately equal to the average of the high-pressure gas and the low-pressure gas. For example, if the pressure in the high-pressure chamber is set for 560 kPa and that in the low-pressure chamber is 140 kPa, the pressure in the diaphragm chamber will be 350 kPa. When all chambers reach designated pressure levels, the gas in the diaphragm chamber is vented to cause the burst of both diaphragms.

The diaphragms need to be carefully machined. In this study, they were made of aluminum 6061 with dimensions of 150 mm x 150 mm and a thickness of 2 mm. Two diagonal groves were machined with a carefully calculated depth to warrant the burst of the diaphragms under the designated pressures. Once, the diaphragms burst, the high-pressure gas flows rapidly into the low-pressure chamber and moves with the low-pressure gas toward the right end of the shock tube. Figures 3(a) and 3(b) show some details of the components of the diaphragm chamber.

At time t_1 after the burst of the diaphragms, several pressure waves occur in the shock tube, as shown in the wave system diagram in Figure 2(c). The shock wave has a magnitude of P_2 with a sharp front preceded by the low-pressure P_1 as shown in Figure 2(d). P_2 is higher than P_1 because the application gas is compressed by the driving gas from behind. A distinct interface separates the two gases (high-pressure and low-pressure). However, the pressure and velocity on both sides of the interface are identical. The pressure behind the interface remains to be P_2 until it is altered by a series of expanding waves, which are formed due to the pressure difference between the driving gas and the application gas. Figure 2(d) shows the pressure change from P_4 to P_2 from the head to the tail of the series of expanding waves.

When the shock wave arrives at the right end of the low-pressure chamber, it reflects from the end cap and turns to the left. The pressure of the reflected shock wave will rise to P_5 as it compresses the incoming shock wave P_2. The head of the expanding waves, on the contrary, moves to the left and is reflected from the end cap of the high-pressure chamber and turns to the right. The tail of the expanding waves has a propagation direction either to the left or to the right depending on the wave pressure and velocity. When the reflected shock wave P_5 meets with the interface, it bounces back and propagates to the right until it is reflected again by the end cap. The second time P_5 meets with the interface, P_5 is increased again because of further compression on the shock wave. P_5 is the output pressure of the shock tube and can be used for further applications such as impact loading and blast loading. The long duration of P_5, as identified by the double-arrow line on the far right of Figure 2(c), is what makes the shock tube interesting for many dynamic testing. Both P_2 and P_5 can be estimated based on the gas pressure and gas properties of P_1 and P_4. Hence, a desired output pressure P_5 can be obtained from adjusting the input gases.

The high-pressure end of the shock tube is usually connected to a gas-tank system while the low-pressure end is connected to a pressure transformer. Based on the shock tube theory and practical experience, various pressure waves can be produced by the shock tube with appropriate combinations of gas components and adjustments of gas pressures. They then can be converted into different pressure sources and used for different types of dynamic testing.

The Pressure Transformer – a piston-like impactor

The shock tube can produce well-defined, pressure waves. In order to demonstrate the superiority of the shock tube over conventional gas guns in generating constant pressure waves, e.g. P_5, with long durations rather than relatively random outputs and to demonstrate the usefulness of the shock waves for advanced dynamic testing, the following impact testing was designed. A steel disk was machined and inserted into the right end of the low-pressure chamber as a pressure transformer as shown in Figure 4. The disk had a diameter slightly smaller than 80 mm of the diameter of the shock tube. No lubricant was applied to the interface between the disk and the tube. A cylindrical tup with a diameter of 18 mm and a length of 100 mm was joined to the disk, resulting in a piston-like impactor with a total mass of 615 g.

Testing Results

In the impact tests, a steel rod having the same diameter as the cylindrical tup and a length of 2,626 mm was used as the testing specimen. It was suspended by two fine strings and aligned with the axis of the tup of the impactor. Four strain gages were mounted on the specimen rod for strain measurements at distances 188mm, 883mm, 1,613mm, and 2,283mm from the impact end.

In the first three tests, nitrogen was used as the driving gas, while air was used as the application gas. The high-pressure P_4 was chosen to be 5 MPa while the low-pressure P_1 was 0.1 MPa. The testing specimen was placed in front of the tup with a gap of 0 mm, 2 mm and 4 mm from the tup. Shown in Figure 5(a) are the shock wave P_2= 0.4 MPa (the initial bump) and the reflected shock wave P_5= 1.5 MPa (the plateau). They were measured with a pressure transducer mounted close to the right end of the low-pressure chamber. Although there is high-frequency noise, the duration of the almost constant pressure P_5 was about 0.8 ms. With a gap of 2 mm between the impactor and the specimen, the velocity of the impactor was measured to be 2.1 m/s. This velocity can be substantially increased with the increase of gas pressures and with the use of other gas components.

The fourth test used a mixture of 50% hydrogen and 50% nitrogen as the driving gas and air as the application gas. The pressure levels were identical to the first three tests. There was no gap between the piston and the specimen. Figure 5(b) shows that the duration of almost constant pressure P_5= 1.3 MPa was about 1.8 ms after an initial shock pressure P_2= 0.2MPa. A rise in P_5 after t= 1.75 ms due to multiple reflections and compressions of the shock wave, as mentioned earlier, can also be seen in the diagram.

Experimental results revealed that the magnitude of strain increased with the increase of the gap between the impactor and the specimen. The steepness of the strain front also increased with the magnitude of the gap. Figures 6 show the measurements of strain from the four strain gages mounted on the steel rod from the fourth test. The duration of the almost constant strain is quite long even for the tup with a length of only 100 mm. It is clear that the long duration of the almost constant pressure P_5 is responsible for this.

Summary

This study was concentrated on an application of a shock tube for impact testing. With proper adjustments of gas components and gas pressures, well-defined, pressure waves were produced. With appropriate design of a pressure transformer, the feasibility of using the shock-tube-based facility for impact testing was demonstrated.

Acknowledgement

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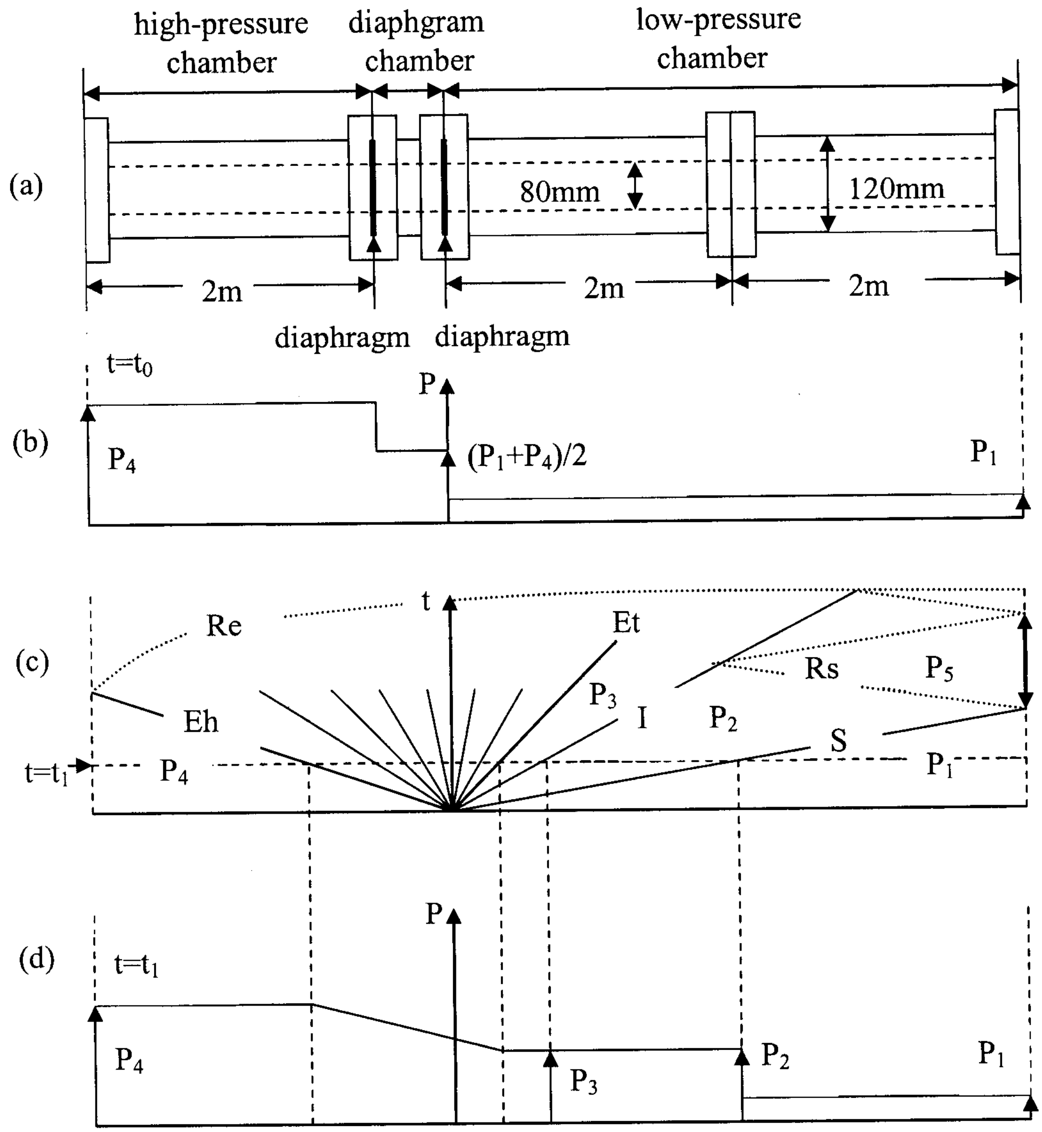
Figure 1 – Pressure generator – the shock tube.



S – shock wave
I – interface
Eh – head of expanding wave
Et – tail of expanding wave
Rs – reflected shock wave
Re – reflected expanding wave

Figure 2 – (a) Schematic diagram and dimensions of shock tube, (b) initial pressure profile, (c) wave system and (d) pressure profile at $t=t_1$.

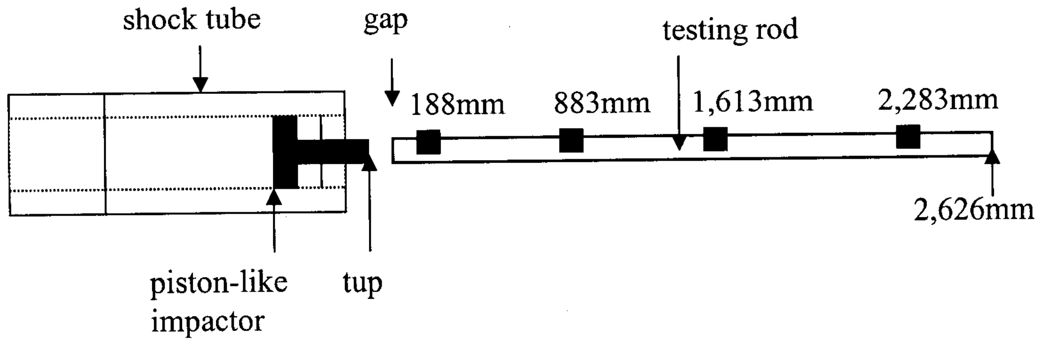


Figure 4 – Pressure transformer – the piston-like impactor.

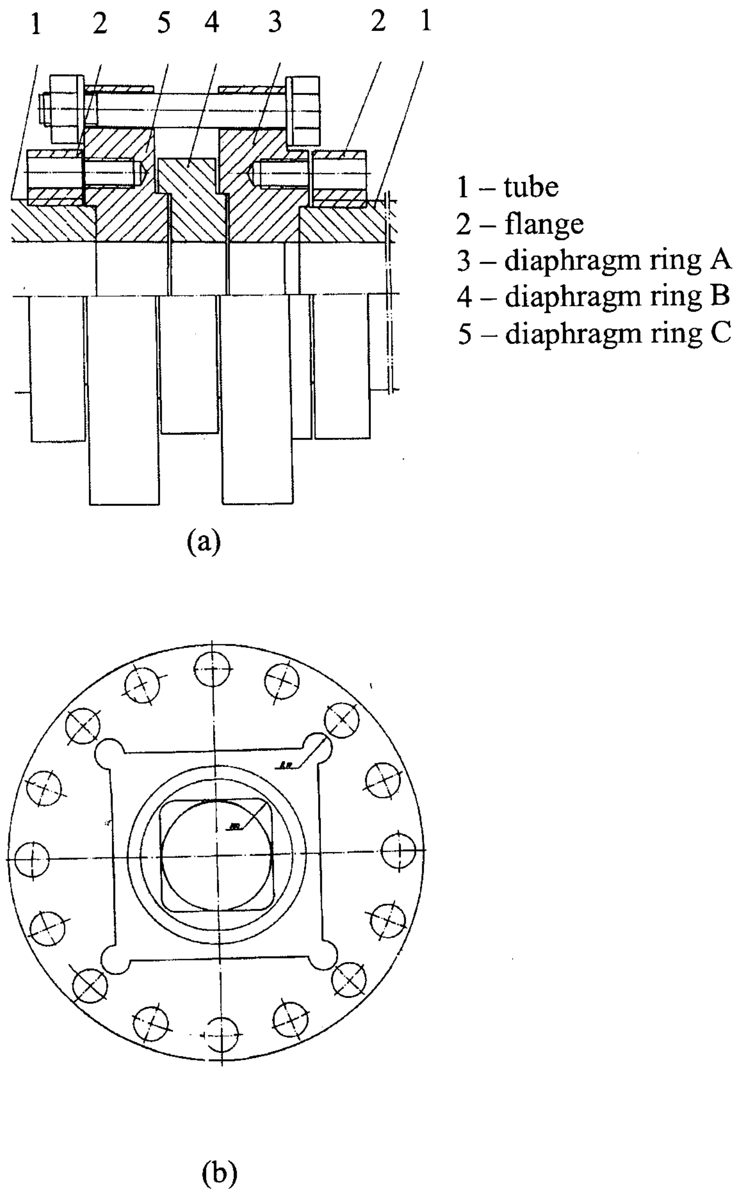


Figure 3 – (a) Details of the diaphragm chamber shown in Figure 2(a) and (b) the cross-section of diaphragm ring A in (a).

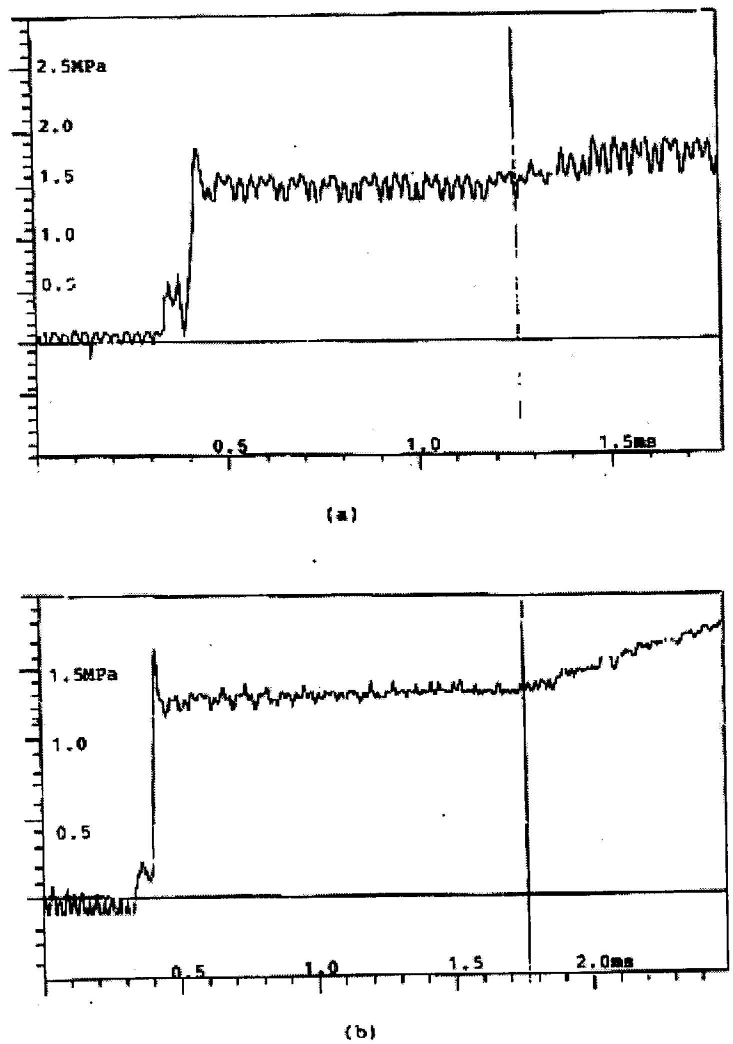


Figure 5 – Pressure P_5 (MPa) as a function of time (ms) based on (a) nitrogen of 5 MPa as driving gas and air of 0.1 MPa as application gas and (b) 5 MPa driving gas consisting of 50% hydrogen and 50% nitrogen and air of 0.1 MPa as application gas.

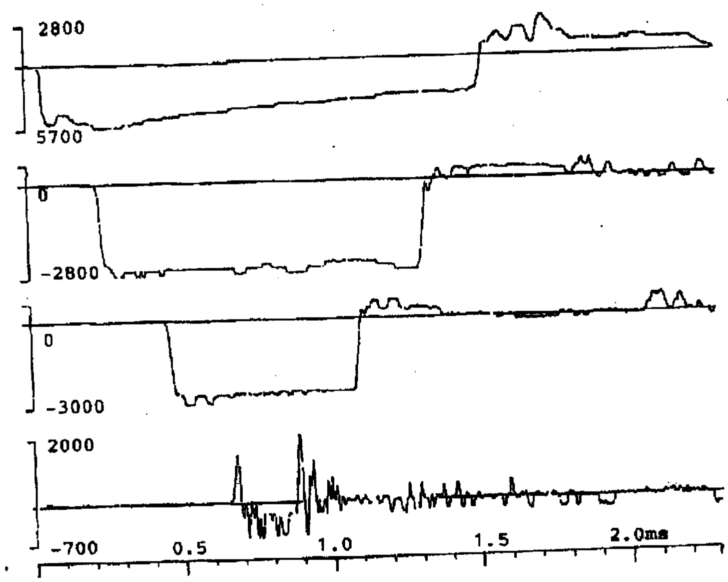


Figure 6 – Measurements of micro-strains from the four gages mounted on the rod subjected to the pressure wave given in Figure 5(b).